An Investigation on Thermal Recycling of Recycled Plastic Resin (Some Experimental Approaches for Reducing Unburnt Particle Emission in the Recycled PET-Resin Powder Combustion)*

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Abstract

The possibility and applicability of thermal recycling of waste PET-resin have been investigated in the open atmospheric operation by supplying PET-resin powder as an auxiliary or additional fuel to the proposed twin-fuelled burner. In the preceding experiments, flow characteristics and burning processes of PET-particles in the proposed burner were investigated using PIV/PTV measurements. Appearances of flying PET-particles were optically observed and analyzed by using the double-pulsed laser, and the particle diameter was evaluated as an equivalent diameter. According to the results, some of the key factors for reducing the unburnt rate of PET-particles were clarified. In this paper, by taking these factors into consideration, an experimental attempt to reduce unburnt particle emission in the PET-resin powder combustion is carried out by varying the diameter of PET-powder supply pipe. The results specify that the increase in the dispersion degree of PET-particles reduces certainly the unburnt rate of PET-powder.

Key words: Heterogeneous Combustion, Thermal Recycling, Waste PET-Resin Powder, Dispersion Degree, Unburnt Rate

1. Introduction

To certify the possibility and applicability of thermal recycling of wasted Polyethylene terephthalate resin powder, which is abbreviated to PET-powder in the following, overall in-furnace combustion characteristics of the propane-fueled industrial burner have been experimentally examined in the model furnace, when PET-powder was supplied as an additional fuel⁽¹⁻³⁾. The results proved that, when PET-powder having a mass median diameter of $d_m \leq 185 \mu\text{m}$ was supplied at a replacement rate of $\alpha \leq 30 \%$, (1) a spatially uniform high temperature field necessary for effective sintering process could be realized, (2) all the PET particles supplied were perfectly consumed and finally disappeared within the furnace due to perfect thermal decomposition and vaporization under high temperature circumstances, and (3) the flexible adjustability of reducing circumstances required in the final stage of sintering process was certified. These characteristics showed positive potential of PET-powder as one of the auxiliary and/or additional fuels in the industrial fields and verified the possibility and applicability of thermal recycling of wasted plastic resin powder.

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However, in the out-of-furnace combustion, on the other hand, a large amount of PET particles up to about 80 % was exhausted as unburnt solid residuals, caused by intense cooling effects of cold circumstances^(4, 5).

It was then necessary to examine and to find some of the key factors which reduce the unburnt solid residuals and improve emission characteristics of the proposed PET-powder combustion. According to the results obtained using a PIV/PTV system^(6, 7), the following three factors were evident; (a) insufficient dispersion of PET particles within the burner due to the inhibitory effect of accelerating gas flow to suppress radial dispersion, (b) insufficient and ineffective heat transfer from the surrounding high temperature combustion gas to PET particles due to biased dispersion concentrated around the burner axis, and (c) insufficient short residence time of PET particles during their passages through the high temperature combustion gas region in the burner. It is indispensable, therefore, for enabling effectively thermal decomposition, vaporization and combustion of PET-powder, not only to realize their full dispersion in the high temperature gas zone as wide as possible, but also to ensure long residence time enough to complete thermal decomposition and gasification.

In this paper, to certify experimentally the effectiveness of these two factors, the effects of the dispersibility of PET-powder in the burner on the amount of unburnt solid residuals are examined. The following factors may be considered to affect directly the PET-powder dispersibility; the diameter of PET-powder supply pipe, the PET-powder mass flow rate, the mean diameter of PET-powder, the inlet air velocity, and the flow pattern in the burner. A model burner is then designed and constructed, which is equipped with an exchangeable PET-powder supply pipe having three different diameters so that the degree of dispersion becomes adjustable. Overall combustion characteristics are first examined using the model burner without PET-powder supply. PET-powder combustion properties are then observed by supplying PET-powder into the model burner. Finally the effects of the dispersion degree on the unburnt rate in the PET-powder combustion are considered.

2. Nomenclature

D	: diameter of PET-powder supply pipe	[mm]
d_m	: mass median diameter of PET-powder	[μm]
l_{min}	: minimum distance between two adjacent PET particles	[μm]
M_C	: unburnt rate collected using the water curtain method	[%]
M_D	: unburnt rate deposited on the burner tube	[%]
M_U	: total unburnt rate of PET-powder	[%]
m_{PET}	: mass flow rate of PET-powder	[g/min]
r	: radial distance from the burner axis	[mm]
u'	: turbulence intensity	[m/s]
T_f	: average flame temperature along the axis	[°C]
t_{PET}	: average residence time of PET particles in the burner tube	[ms]
V_{PET}	: PET particle velocity	[m/s]
v_{AN}	: main air velocity	[m/s]
v_{PET}	: velocity of air flow for PET-powder conveyance	[m/s]
x_i, y_i	: coordinates of the center of gravity of i -th PET particle	[μm]
z	: axial distance from the burner exit	[mm]
ϕ_{AN}	: equivalence ratio of propane-air flame	[-]
ϕ_{PET}	: equivalence ratio of PET-powder flame	[-]

3. Experimental Apparatus and Methods

3.1 Experimental Apparatus

The schematic diagram of the experimental apparatus is shown in Fig. 1. The system is composed of a proposed twin-fueled burner, a main air supply line, a propane supply line, a PET-powder supply line, and a set of measuring instruments. Commercial grade gaseous propane having a purity of 96.4 % is used as a main fuel. PET-powder which is sieved in the diameter range of $100 \mu\text{m} \leq d \leq 180 \mu\text{m}$ and has a lower heating value of 21.8 MJ/kg and a density of $1.38 \times 10^3 \text{ kg/m}^3$ is employed as an additional fuel.

The construction and dimensions of the proposed burner are shown in Fig. 2, where details and dimensions of the burner exit are presented as three expanded insets. The main part of the proposed burner is concentric and consists of a brass tube having an inner diameter of 28 mm and a PET-powder supply pipe, the latter being interchangeable in three pipes having inner diameters of 10, 14 and 17 mm. A ring-type flame stabilizer made of brass wire of 1 mm diameter is set flush with the exit section of the PET-powder supply pipe. Propane and main air are supplied through four radial connecting tubes installed at the upstream end of the burner at 90 degree intervals, whereas PET-powder is conveyed axially using a propane-air mixture into the supply line at the upstream end of the burner. A quartz glass tube of 28 mm inner diameter and 200 mm length is used as a burner tile to allow direct and optical observations of PET-powder flame characteristics.

To adjust the degree of PET-powder dispersion, the diameter of PET-powder supply pipe is varied in three kinds, 10 mm, 14 mm and 17 mm, as shown in the insets (a) ~ (c) in Fig. 2. A ring honeycomb having a length of 110 mm is installed in the PET-powder supply pipe, so that the difference in the pipe diameter does not alter turbulence properties of the inner mixture stream for PET-powder conveyance. The r - z coordinate system used in this

Fig. 1 Schematic diagram of the overall experimental apparatus

Fig. 2 Construction and dimensions of the proposed burner

Table 1 Setting conditions of inner and annular propane-air mixture flows

Diameter of PET powder supply pipe D [mm]	Inner mixture stream		Annular mixture stream	
	Velocity v_{PET} [m/s]	Equivalence ratio ϕ_{PET}	Velocity v_{AN} [m/s]	Equivalence ratio ϕ_{AN}
10	3.8	0.9	3.8	0.9
14				
17				

experiment is also given in Fig. 2.

3.2 Experimental Procedure and Methods

Basic flames without PET-powder supply are first examined to elucidate the effects of the diameter of PET-powder supply pipe on their properties. The setting conditions for three basic flames are summarized in Table 1, where D indicates the diameter of PET-powder supply pipe, and v and ϕ mean the average velocity and the equivalence ratio of two types of mixture flows. As shown in Table 1, the average velocity of inner mixture stream for PET-powder conveyance and the annular main mixture stream are set to an equal value of $v_{PET} = v_{AN} = 3.8$ m/s, and the equivalence ratios for the two mixture streams are assigned to a common constant value of $\phi_{PET} = \phi_{AN} = 0.9$. Direct photographs of the three basic flames are taken using a digital camera and temperature profiles along the burner axis are measured using an R-type fine thermocouple of a diameter of 0.1 mm. No compensation is made for the measured temperature. To examine the effects on the basic flame properties, sectional profiles of absolute turbulence intensity in the cold flows without combustion are measured using a hot-wire anemometer equipped with an I-type probe of 5 μ m Tungsten wire.

The schematic diagram of PTV system is shown in Fig. 3. Since the PET-powder flame generates not only intense spontaneous emission from the yellow diffusion flame, but also high-speed gas flow up to about 10 m/s in the measuring section, it is necessary to employ such a light source as to enable the consecutive pulse emission having sufficient intensity and extremely short intervals. In this system a double-pulsed Nd:YAG laser (Continuum CLP10PIV) having a resonance wavelength of 532 nm, an output of 220 mJ/pulse, and a minimum pulse interval of 5 ns is employed and combined with a high-speed CCD video camera. After passing through an optical lens system, the laser-light enters into the objective region as a light sheet of 0.3 mm thickness and 50 mm width. To avoid reflection of the spontaneous emission from the yellow diffusion flame to PTV images, an interference filter having a central wavelength of 532 nm and a transmissivity of 80 % is installed in front of the CCD video camera. PET particles sieved in the diameter range of $d = 100 \sim 180$ μ m are used as tracer particles in the PTV measurements in the PET-powder flames.

Combustion characteristics of PET-powder flames are then observed and analyzed using the PTV system, when the diameter of PET-powder supply pipe is interchanged. Unburnt solid residuals are collected using the water-curtain method⁽⁷⁾ and weighed. Based

Fig. 3 Schematic diagram of the PTV system used

on a set of PTV images, sectional dispersion profiles of PET particles across the burner, sectional velocity vector fields of PET particles and variation of average residence time are estimated. The minimum distance between two adjacent particles is also analyzed using PTV images, since it is qualitatively inversely proportional to the dispersion degree and considered to be a reasonable measure of dispersion degree. The influences of the PET-powder dispersion degree on the unburnt solid residuals are finally considered, based on the results obtained in this paper.

4. Results and Discussion

4.1 Combustion Characteristics of Basic Flames

4.1.1 Direct Photographs of Basic Flames

Direct photographs of three basic flames are shown in Fig. 4, where the diameter of PET-powder supply pipe is set to (a) $D = 10$ mm, (b) $D = 14$ mm and (c) $D = 17$ mm. The overall equivalence ratio is adjusted to $\phi = 0.9$. The broken line indicates the inner boundary of the quartz glass tube. Figure 4 shows that a conical blue flame is developed downstream of a small V-shaped ring flame and has a length of about 80 mm, independent of the PET-powder supply pipe diameter. It is found, therefore, that the change of diameter D does not affect the fundamental appearances of basic flames.

4.1.2 Temperature Profiles along the Axis

Temperature profiles along the axis of the three basic flames given in Fig. 4 are shown in Fig. 5, where the ordinate gives the average temperature T_f and the abscissa means the axial distance from the burner exit z , and the symbols $\circ$, $\triangle$ and $\square$ indicate that the PET-powder supply pipe diameter D is assigned to 10 mm, 14 mm and 17 mm.

It is found that the temperature increases steeply in the upstream region of $z = 30 \sim 80$ mm, corresponding to the formation of conical flame, and is kept almost constant in the range of $1450 \sim 1500$ °C in the intermediate and downstream region of $z = 80 \sim 260$ mm. In further downstream region, the temperature decreases gradually due to the entrainment and cooling effect of ambient cold air. These characteristic behaviors are found to be almost independent of the diameter of PET-powder supply pipe D .

Fig. 4 Appearances of three basic flames without PET-powder supply ($\phi = 0.9$)

Fig. 5 Temperature profiles along the central axis

4.1.3 Sectional Profiles of Turbulence Intensity in the Upstream Region

Turbulence intensity profiles across three typical sections in the upstream region of the cold flow without combustion are measured using a hot-wire anemometer under the same setting conditions as those in Fig. 4. The results are given in Fig. 6 for the axial position; (a) $z = 1$ mm, (b) $z = 15$ mm and (c) $z = 30$ mm, where the ordinate gives the radial distance and the abscissa indicates the absolute turbulence intensity. The meanings of three symbols are the same as those in Fig. 5. The numbers ①~③ assigned to three sets of broken lines show the inner diameter of PET-powder supply pipe is $D = 10, 14$, and 17 mm.

Figure 6 shows that the profiles of turbulence intensity for three pipe diameters differ partially from each other to some extent which may result from the combined effects of the boundary layers at both sides of the pipe and the wake flows behind the rod stabilizer and the pipe end. There are something in common with each other, however, that the turbulence intensity has a common range of $u' = 0.1 \sim 0.4$ m/s independent not only on the sections but also on the PET-powder supply pipe diameter. The latter fact suggests that the turbulence characteristics obtained do not depend on the diameter of PET-powder supply pipe and that, therefore, they affect almost little difference on the conveyance and dispersion performance due to turbulence mixing in the upstream region of the burner.

4.2 PET-Powder Combustion Characteristics in the Improved Twin-Fueled Burner

In the preceding paragraph it is certified experimentally that the change of the diameter of PET-powder supply pipe exerts almost no influence on the turbulence and combustion characteristics of the basic model burner. In this paragraph, therefore, the main attention is paid on the effects of the pipe diameter on the extent of PET-powder dispersion.

4.2.1 Behavior of PET-Powder Flames

Three kinds of PET-powder flames are presented in Fig. 7 for the diameter of PET-powder supply pipe of (a) $D = 10$ mm, (b) $D = 14$ mm and (c) $D = 17$ mm, respectively. The mass flow rate of PET-powder is assigned to $m_{PET} = 9.6$ g/min, resulting in the overall equivalence ratio of $\phi = 1.34$ and the overall heat output of 12.8 kW. According to Fig. 7, the flame length becomes longer and the effect of buoyancy becomes more remarkable as the pipe diameter becomes large from $D = 10$ mm to 17 mm. Also observed is that a cluster of dense and sooty flame region becomes more prominent as D increases. On the contrary, reduction of multiple stripes of loci of unburnt solid particles in the flame tip region is apparent as the diameter increases. These results suggest the certain possibility to reduce the unburnt solid particle emission by increasing the diameter of PET-powder supply pipe.

4.2.2 Dispersion Profiles of PET Particles in the Upstream Region

Fig. 6 Turbulent intensity profiles at three cross-sections

The effects of the diameter of PET-powder supply pipe on the dispersion profiles of PET particles in the lateral section including the burner axis can be seen in Fig. 8, where the diameter of PET-powder supply pipe is (a) $D = 10$ mm, (b) $D = 14$ mm and (c) $D = 17$ mm. The ordinate gives the radial distance from the axis and the abscissa the axial distance from the exit of the PET-powder conveyance pipe. The white square of $10 \text{ mm} \times 10 \text{ mm}$ depicted in each PTV image presents the objective test section, which will be used for evaluating the minimum distance between two adjacent PET particles and discussed later in this paper.

Fig. 7 PET-powder flame appearances at a mass flow rate of $m_{\text{PET}} = 9.6 \text{ g/min}$

Fig. 8 Examples of PTV measurements along the lateral cross section including the central axis

Taking account of the curvature of quartz glass pipe in the upper and lower edge zones of the images and paying main attention to the images around the axis, it can be found that the extent of PET particle dispersion in the image of (a) $D = 10$ mm is restricted to the central zone around the axis, as compared with those in the images of (b) $D = 14$ mm and (c) $D = 17$ mm. The increase in the diameter of PET-powder supply pipe D , therefore, is considered to have a definite tendency to disperse widely PET particles.

4.2.3 Cumulative Distributions and Sectional Histograms of PET Particles

After processing such PTV data as given in Fig. 8 and integrating over 100 processed images, cumulative distributions of PET particles across the lateral section including the burner axis are obtained. The results are presented in the upper half of Fig. 9(a) ~ (c) for the two axial regions of $z = 0 \sim 75$ mm $150 \sim 200$ mm. The diameter of PET-powder supply pipe D is assigned to (a) 10 mm, (b) 14 mm and (c) 17 mm. In the lower half of each figure, five sectional histograms are given by integrating all PET particles over five lateral zones of $z = 0 \sim 25$ mm, $25 \sim 50$ mm, $50 \sim 75$ mm, $150 \sim 175$ mm and $175 \sim 200$ mm. The numbers at the right-upper of histograms give the total number of PET particles used to accumulate the histogram in each lateral zone. The ordinate of Fig. 9 indicates the radial distance and the abscissa of histogram indicates the percentage of the probability in the radial region in 2 mm intervals. In processing PTV data, the particle position is determined by calculating the coordinates of the center of gravity of all PET particles in each PTV image.

According to overall distributions in the upstream region of $z = 0 \sim 75$ mm, the PET particle dispersibility becomes notable as the pipe diameter D increases. This tendency can be certified in the variation of histogram profiles; peaked profiles around the axis for $D = 10$ mm, while wide and flat profiles for $D = 14$ and 17 mm. According to overall distributions and histograms in the downstream region of $z = 150 \sim 200$ mm, on the other hand, almost

Fig. 9 Variation of cumulative distributions and histograms of PET particles along the lateral cross section including its axis with the diameter of PET-powder supply pipe D

no difference is apparent, except that the histograms in $D = 17$ mm become rather flat. It is considered, therefore, that the dispersibility of PET-powder in the downstream region does not largely depend on the diameter of PET-powder supply pipe.

By the way, a remarkable difference is apparent between the particle numbers counted in the upstream region and those in the downstream region. This difference is considered to result from the consumption of PET particles due to thermal decomposition, evaporation and combustion during their passages through the flame zone.

4.2.4 Variation of Average Velocity Vectors of Frying PET Particles

Average velocity vector distributions are obtained by processing statistically all the data given in Fig. 9 and averaging them in the axial ranges of 10 mm intervals. The results obtained in the upstream and downstream axial regions of $z = 0 \sim 50$ mm and $150 \sim 200$ mm are indicated in the left and right halves of Fig. 10, respectively, for (a) $D = 10$ mm, (b) $D = 14$ mm and (c) $D = 17$ mm, where the ordinate means the radial distance from the axis and the abscissa gives the axial distance from the exit of the PET-powder supply pipe. In the left half vector diagrams the outlines of conical blue flames are depicted using a set of chain lines, based on the direct photographs of the basic flames shown in Fig. 4.

Figure 10 shows that, in the upstream region of $z = 0 \sim 50$ mm, PET particles passing through the flame zone are accelerated and refracted radially outward due to the effects of local reaction and thermal expansion. In the downstream region of $z = 150 \sim 200$ mm, on the contrary, high temperature combustion gas tends to form a unidirectional confined pipe flow having relatively uniform vector profiles. These characteristics are common to three vector diagrams in Fig. 10 and almost independent on the diameter of PET-powder supply pipe, except that PET particles are widely dispersed and the objective region of velocity vector measurement becomes wider with the increase in the diameter D .

4.2.5 Rough Estimation of Average Residence Time in the Burner Tube

The mean axial velocity of PET particles V_{PET} is evaluated by simply averaging all the

Fig. 10 Mean velocity vector profiles across the sections

Fig. 11 Mean velocity variations of flying PET particles

PET particle velocities in the objective section normal to the burner axis. The axial velocity is plotted against the axial distance in Fig. 11, where the diameter of PET-powder supply pipe is varied as a parameter, $\circ$: $D = 10$ mm, $\triangle$: $D = 14$ mm and $\square$: $D = 17$ mm.

According to Fig. 11, the sectional averaged velocity of PET particles increases almost linearly with the axial distance z from $V_{PET} \approx 2$ m/s at the exit of PET-powder supply pipe to $V_{PET} = 8 \sim 9$ m/s at the axial position of $z = 150$ mm and, then, gradually increases and approaches to a constant value of $V_{PET} \approx 10$ m/s at the exit of the burner. This behavior is found to be a characteristic common independent of the pipe diameter D . The average residence time of PET particles in the burner tube is then roughly estimated, based on the variation of axial PET particle velocity shown in Fig. 11, $t_{PET} = 36.0$ ms for $D = 10$ mm, $t_{PET} = 36.9$ ms for $D = 14$ mm and $t_{PET} = 39.2$ ms for $D = 17$ mm. These values distribute within a very small deviation of $\pm 5\%$ at most around a simply averaged value of $t_{PET} = 37.4$ ms. It is concluded that the diameter of PET-powder supply pipe does not exert direct influence on the mean residence time, and that its direct influence on the amount of unburnt solid residuals is also negligible small.

4.2.6 Behavior of Minimum Distance between Two Adjacent Particles

When heat transfer characteristics from the surrounding hot combustion gas to PET particles are considered, it is indispensable to evaluate the distance between two adjacent particles. An objective square window having a side of 10 mm, which was already indicated in Fig. 8 as a test section, is set just downstream of the exit of PET-powder supply pipe. This is because that the diameter of PET-powder supply pipe exerts most prominent effect on the degree of particle dispersion at the section.

An example of expanded PTV images taken at the test section is given in Fig. 12 in the x - y coordinate system. PET particles having wide variety of sizes and shapes can be seen in Fig. 12. Assigning the coordinates of the center of gravity, indicated by red points, of two arbitrary adjacent PET particles as (x_i, y_i) and (x_j, y_j) based on image processing, as shown in the left-upper part of Fig. 12, the distance between two arbitrary adjacent PET particles is calculated using the following expression.

$$l_{ij} = [(x_i - x_j)^2 + (y_i - y_j)^2]^{1/2} \quad (1)$$

The distance is calculated for all particles photographed in each PTV image and the minimum distance is picked up among them. This image processing is repeated for 100 PTV images and the cumulative distributions of the minimum distance are constituted for the three pipe diameters of PET-powder supply pipe; $D = 10, 14$ and 17 mm. The results are presented in Fig. 13 by the symbols $\circ$, $\triangle$ and $\square$, respectively, where the ordinate gives the cumulative rate and the abscissa indicates the minimum distance, l_{min} .

Figure 13 shows clearly that the cumulative distribution of minimum distance entirely shifts to the right-hand side as the diameter of PET-powder supply pipe increases, and that the minimum distance for $D = 10$ mm is smaller than the other two. Also shown is that the profile for $D = 17$ mm distributes in the larger range than that for $D = 14$ mm. These clear

Fig. 12 An example of PTV images;
Distance between two adjacent
PET particles

Fig. 13 Minimum distance between two
adjacent PET particles

tendencies suggest the following qualitative scheme for improving the unburnt particle emission characteristics. The larger the diameter of PET-powder supply pipe becomes, the greater the minimum distance between two adjacent particles becomes and, therefore, the more effectively the heat and mass transfer to and from the surrounding combustion gas is promoted. The heat transfer enhancement augments in turn a series of elementary processes from solid heating to thermal decomposition and vaporization, and finally makes possible the reduction of unburnt particle emission by going hand in hand with the mass transfer enhancement of excess oxygen to particles.

4.2.7 Behavior of Unburnt Particle Emission

The variation of PET-powder unburnt rate is presented in Fig. 14, when the diameter of PET-powder supply pipe is changed as a parameter. The unburnt rate M_U [%] is defined by dividing the mass of unburnt PET-powder collected by the total mass of PET-powder supplied, where the former consists of the unburnt mass collected using the water curtain method⁽⁷⁾, M_C [%] and that deposited to the burner tube, M_D [%].

According to Fig. 14, the unburnt rate for $D = 10$ mm takes a large value of $M_U \approx 13$ %, whereas those for $D = 14$ and 17 mm are $M_U = 6$ and 4 %, respectively, being less than half of that for $D = 10$ mm. It is concluded, therefore, that the increase in the diameter of PET-powder supply pipe can realize the reduction of unburnt particle emission, through the improvement of PET-powder dispersibility, the increase in the particle distance, and the heat transfer enhancement. By the way the unburnt mass deposited to the burner tube only accounts for 2 % at most, indicating that the proposed burner can realize direct and effective supply of PET-powder into the flame zone almost without fusion in the supply pipe.

Fig. 14 Variations of PET-powder unburnt rate with the diameter of
PET-powder supply pipe

5. Concluding Remarks

In this paper the experimental burner is first proposed, which enables to adjust the PET-powder dispersibility by changing only the diameter of PET-powder supply pipe, and the overall characteristics of the proposed burner are observed. The influences of PET-powder dispersibility on the unburnt PET particle emission behavior are then examined, when PET-powder is supplied to the burner as an additional fuel. The results obtained in this paper are summarized as follows.

(1) Basic combustion characteristics of the proposed burner without PET-powder supply, such as the main propane-air flame appearances, average temperature profiles along the flame axis and turbulence properties without combustion exhibit negligibly small influence of the diameter of PET-powder supply pipe. It is suggested that the improvement of the degree of PET-powder dispersion due to the increase in the diameter of PET-powder supply pipe is of prime importance.

(2) The dispersion images of PET particles, spatial provability distributions of PET particles, average velocity profiles in the axial direction, and the cumulative distributions of the minimum distance between two adjacent particles are measured and analyzed based on various PTV measurements and their data processing. The results clearly indicate quick and effective dispersion of PET particles in the early stage of their passages through the flame zone as the diameter of PET-powder supply pipe increases.

(3) The behavior of PET-powder unburnt rate is examined by varying the diameter of PET-powder supply pipe. The results show that the unburnt rate obtained for $D = 17$ mm is reduced to about one third of that for $D = 10$ mm. This experimental fact clarify that the improvement of PET-powder dispersibility due to the increase in the diameter of PET-powder supply pipe reduces the unburnt solid residuals.

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